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(73) Proprietor: **International Business Machines Corporation**
Old Orchard Road
Armonk, N.Y. 10504 (US)

(72) Inventor: **Harder, Christoph Stephan, Dr.**
Immenweg 12
CH-8050 Zürich (CH)

Inventor: **Stoll, Erich Paul, Dr.**
Weidelacherstrasse 1
CH-8143 Stallikon (CH)

Inventor: **Pohl, Wolfgang Dieter, Dr.**
Felsenhofstrasse 10
CH-8134 Adliswil (CH)

(74) Representative: **Rudack, Günter O., Dipl.-Ing.**
IBM Corporation Säumerstrasse 4
CH-8803 Rüschlikon (CH)

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Description

This invention relates generally to the art of optical microscopy and in particular to the design of the objective aperture for an optical near-field scanning microscope.

Optical microscopes have a long history and their application has since long extended beyond research and the physician's practice. The search for viruses and bacteria as well as the manufacture of electronic circuits require microscopes of ever better resolution. The theoretical limit for the resolution of an optical microscope lies in the range of the wavelength of the light used, i.e. about 500 nm, since direct human inspection naturally requires visible light. The distance between two object points which an optical microscope can just resolve, when the illumination is incoherent and the microscope's aperture is circular, is $\sim 0{,}61\ \lambda/n \cdot \sin\theta$, wherein $n \cdot \sin\theta$ is the numerical aperture of the objective lens, i.e. the product of the refractive index of the glass n and of the semi-angle θ of the cone of rays in the object space. Obviously, the numerical aperture should be large if a high resolving power is to be achieved (M. Born and E. Wolf, Principles of Optics, Pergamon Press, London 1959, p. 417f).

Numerous attempts to increase the resolving power of microscopes are known from the prior art. The most important achievements relative to the subject of the present invention have been disclosed in EP—A1—0112401 and EP—A1—0112402. The first-mentioned reference is directed to an optical near-field scanning microscope in which the "objective" consists of an optically transparent crystal having a metal coating with an aperture at its tip, the diameter of the aperture being considerably smaller than one wavelength of the light used for illuminating the object.

The second-mentioned reference, EP—A—0112402 concerns a light waveguide with an aperture the diameter of which is between 10 and 500 nm, and a method for manufacturing such a waveguide. This waveguide too, consists of an optically transparent body which is coated with a multi-layer metal film.

The references cited above suggest the use of the objective either as an observing instrument looking at the object which is illuminated by some external light source, or inversely, the illumination is shone through the objective and the radiation reflected by the object is detected by a separate detector. While in both cases the purpose of increasing the resolution through reduction of the diameter of the objective is served, the disadvantages, however, are a very noisy picture on the one hand and a rather bulky apparatus on the other. It is an object of the present invention to teach an optical aperture which overcomes these disadvantages while at the same time maintaining the narrowness of the aperture and the ease of the manufacture.

Accordingly, the aperture of the present invention comprises an optically transparent body coated with a first opaque layer except for a small area at the front end thereof, with the characteristic that said first opaque layer is at least partly covered with a layer of an optically transparent medium which in turn is covered with a second opaque layer, except for a small area to the side of the small area of said transparent body, such that light entering the transparent body from the back can exit through the small area at the front end thereof and be directed onto an object and that light reflected by said object can enter said transparent layer through the small area thereof and be guided to a light detector to which the transparent layer is optically connected.

Details of several embodiments of the invention will be described by way of example with the aid of the attached drawings in which:

Figure 1 is a schematic representation of a conventional optical near-field scanning microscope;

Figure 2 is cross-section of one embodiment of the aperture in accordance with the invention;

Figures 3 through 5 show embodiments with a transparent body having a square cross-section;

Figures 6 and 7 represent embodiments of an aperture comprising optical fibers.

Figure 1 shows the basic elements of an optical near-field scanning microscope as it is known from EP—A1—0112401. Briefly, a frame 1 is secured to a bench 2 which also carries a support 3 arranged for x/y movement of an object 4 to be inspected. An arm 5 of frame 1 carries a vertical adjustment appliance 6 for controlling the distance of an aperture 7 from object 4 with the aid of a sensor 8. Attached to aperture 7 is an optical filter 9 which in turn is connected, via a light guide 10, to a photodetector 11. This arrangement assumes illumination of object 4 by an external light source, be it in reflection or transmission modes.

In an inverse arrangement, photodetector 11 would be replaced by a suitable light source, such as a laser, and the light reflected from the object would have to be collected by a separate light detector 12.

As mentioned before the present invention contemplates the integration of light source and detector in the vicinity of the object in order to reduce any disturbances that may be caused by the ambient light or stem from parts of the object other than that very part onto which the aperture is directed.

Referring to Figure 2, an optically transparent body 13 is conventionally coated with an opaque layer 14. Body 13 may consist of a quartz crystal, for example, and carry a metal coating the thickness of which should be a few times the optical penetration depth, i.e. about λ/10 for visible light. Alternatively, body 13 may be the end of an optical fiber with the cladding removed. Body 13 should be pointed as sharply as possible, the radius of curvature of its tip being in the neighbourhood of 20 nm, for example. Methods to produce such sharply pointed transparent bodies are disclosed in EP—A1—0112402. An alternative method is ion milling.

Opaque layer 14 in itself may consist of a single

coating of metal or of a plurality of metal coatings, as described in EP—A1—0112402, for better adhesion to the crystal or fiber material. Layer 14 carries a transparent layer 15 just thick enough to permit non-overdamped optical waveguiding, i.e. having a thickness on the order of $\lambda/2$, and tapered towards the apex to a thickness of about $\lambda/20$. A second opaque layer 16 is placed around transparent layer 15, and this may again consist of metal. The thickness of the second metal layer is not critical; it should be in the range of tenfold the penetration depth of the metal used. Of course, this layer may consist of several coatings of different metals, as in the case of layer 14. All of these layers 14 through 16 carried by body 13 can be produced by evaporation, sputtering, or other conventional thin film techniques.

Transparent layer 15 enclosed between opaque layers 14 and 16 forms a light waveguide for the radiation entering its annular aperture 17 after reflection by the object 4 of the rays exiting from a central aperture 18. The tapered shape of transparent layer 15 with a thickness below the wavelength of the light used favours the propagation of the reflected radiation in form of the TEM_{01} mode which has no sharp cutoff at sub-wavelength dimensions. (For the TEM_{01} mode cf. D. Pohl Operation of a Ruby Laser in the Purely Transverse Electric Mode TE_{01}, Appl. Phys. Lett., Vol. 20, No. 7, April 1, 1972, p. 266f).

The waveguide 14, 15, 16 may be connected directly to a set of distributed photodetectors concentrically arranged around transparent body 13, or to an annular photodiode 19.

While Figure 2 assumes a circular cross-section for transparent body 13, which would particularly apply to an optical fiber, Figures 3, 4 and 5 show a transparent body with a square cross-section. In Figure 3, body 20 is partly covered with a transparent layer 21 over a metallization (not shown), the transparent layer 21 being tapered such that light entering through the four-sided aperture 22 is guided into a photodetector 23. The outer metallization of layer 21 is not shown for clarity of the figure.

Another embodiment is shown in Figure 4 where the square body carries four independent waveguides 24, 25, 26, (waveguide 27 not shown) each ending in an individual photodetector 28, 29, 30 (photodetector 31 not shown). Light emitted from the central aperture 32 and reflected by the object enters into the four rectangular apertures 33 through 36 and is conducted, by the respective one of associated waveguides 24 through 27, to one of said photodetectors 28 through 31. This arrangement is particularly useful for differential microscopy by comparison of the output signals of oppositely located photodetectors.

Figure 5 shows yet another embodiment with a transparent body 37 having a square cross-section. Light having exited through a central aperture 38 in the body after reflection by the object enters through apertures 39 and 40. The light waves propagating up wave guides 41, 42 are brought to interference at the joint 43 of waveguides 41 and 42. An electrooptic phase shifter 44 permits the adjustment of the relative phases of the arriving light waves. Joint 43 of the waveguides 41 and 42 preferably has a monomode cross-section. This arrangement provides differential phase information. In other words, it introduces phase contrast methods into optical near-field scanning microscopy. To measure this phase contrast signal, a photodetector 45 is connected to joint 43.

In Figures 6 and 7 implementations of the invention making use of glass fibers are shown. A glass rod 46 (Figure 6) is connected to a light source (not shown) and emits light through an aperture 47. Rod 46 may be realized by a glass fiber. Attached to rod 46 is a glass fiber 48 with its end tapered to about $\lambda/20$ and metallized. Its aperture 49 receives the reflected light which is guided to a detector, not shown.

Figure 7 is an arrangement with glass fibers in a configuration similar to the one shown in Figure 4. Around a central glass rod or fiber 51 having an aperture 50 at one end, are arranged four receiving glass fibers 52 through 55 with their ends tapered to about $\lambda/20$ as explained in connection with Figure 6 and defining apertures 56 through 59, respectively. This arrangement allows for differential reflectivity and differential phase contrast microscopy.

In the arrangements of Figures 6 and 7, the spaces between the waveguides may be filled with a low-melting metal.

If the light source used to illuminate the object is chosen to be a laser, the man skilled in the art may elect to integrate the laser into the transparent body of Figures 2 through 5. This can be easily done with a semiconductor laser in accordance with the teaching of EP—A1—0112402.

While the invention has been described in connection with an optical near-field scanning microscope, it will be self-evident for those skilled in the art that the waveguides in accordance with the invention can find application in connection with endoscopes used for the inspection of cavities, be it in living organisms or in natural or man-made devices and machines.

Claims

1. Aperture for an optical near-field scanning microscope, comprising an optically transparent body (13, 20, 37) coated with a first opaque layer (14) except for a small area (18, 32, 38) at the front end thereof, characterized in that said first opaque layer (14) is at least partly covered with a layer (15, 21, 26, 41, 42) of an optically transparent medium which in turn is covered with a second opaque layer (16) except for a small area (17, 22, 33...,36, 39, 46) to the side of the small area (18, 32, 38) of said transparent body (13, 20, 37), such that light entering the transparent body (13, 20, 37) from the back can exit through the small area (18, 32, 38) at the front end thereof and be directed onto an object (4), and that light reflected by said object (4) can enter said transparent layer

(15, 21, 24...27, 41, 42) through the small area (17, 22, 33...36, 39, 40) thereof and be guided to a light detector (19, 23, 28...31, 45) to which the transparent layer (15, 21, 24...27, 41, 42) is optically connected.

2. Aperture for an optical near-field scanning microscope, comprising a first optically transparent body (46, 51) coated with an opaque layer except for a small area (47, 50) at the front end thereof, characterized in that at least one second, pointed, optically transparent body (48, 52...55) which is coated with an opaque layer except for a small area (49, 56...59) to the side of the small area (47, 50) of said first transparent body (46, 51), is arranged in juxtaposition with said first transparent body (46, 51), such that light entering said first transparent body (46, 51) from the back can exit through the small area (47, 50) at the front end thereof and be directed onto an object (4), and that light reflected by said object (4) can enter said second transparent body (48, 52...55) through the small area (49, 56...59) thereof and be guided to an associated light detector.

3. Aperture in accordance with Claim 1, characterized in that the optically transparent layer (15, 21, 24...27, 41, 42) is tapered towards its small area (17, 22, 33...36, 39, 40) to a thickness of about one twentieth of the wavelength of the light used.

4. Aperture in accordance with Claim 2, characterized in that the second transparent body (48, 52...55) is tapered towards its small area (49, 56...59) to about one twentieth of the wavelength of the light used.

5. Aperture in accordance with Claim 1, characterized in that said transparent body (20) has a rectangular cross-section and is partly covered with a transparent layer (21) on top of said first opaque layer, the transparent layer (21) being bevelled such that a light wave entering through its small area (22) is guided to a single light detector (23) connected to said transparent layer (21).

6. Aperture in accordance with Claim 1, characterized in that the sides of said transparent body (20) are provided with two or more transparent layers (24...27), each of which being connected to an associated light detector (28...31) at one end, and at the other forming small areas (33...36) arranged about the small area (32) on the transparent body (20) in a symmetrical configuration.

7. Aperture in accordance with Claim 6, characterized in that the transparent body (20) has a square cross-section, and that four light guides (24...27) end in small areas (33...36) arranged in a cross-like configuration.

8. Aperture in accordance with Claim 1, characterized in that said transparent layer (15) is optically connected to a circular light detector (19).

9. Aperture in accordance with Claim 1, characterized in that said transparent body (37) on opposite sides, on top of its opaque layer, carries a pair of transparent layers as light guides (41, 42) connected in a joint (43) leading to a light detector (45), one of said light guides (41, 42) being provided with an optical phase shifter (44).

10. Aperture in accordance with Claim 9, characterized in that said light guides (41, 42) have small areas (39, 40) respectively situated on both sides of the small area (38) of said transparent body (37).

11. Aperture in accordance with Claim 2, characterized in that said first transparent body (46, 51) and said second transparent body (48) or bodies (52...55) are surrounded by an optical material, namely low-melting metal.

12. Aperture in accordance with Claim 2, characterized in that said first transparent body (46, 51) and/or the second transparent body (48) or bodies (52...55) consists of glass fibers.

Patentansprüche

1. Apertur für ein optisches Nah-Feld Abtastmikroskop mit einem optisch transparenten Körper (13, 20, 37), der mit einer ersten opaken Schicht (14) überzogen ist, mit Ausnahme einer kleinen Fläche (18, 32, 38) an seinem vorderen Ende, dadurch gekennzeichnet, daß die genannte erste opake Schicht (14) wenigstens teilweise mit einer Schicht (15, 21, 26, 41, 42) eines optisch transparenten Mediums überzogen ist, das seinerseits mit einer zweiten opaken Schicht (16) bedeckt ist, mit Ausnahme einer kleinen Fläche (17, 22, 33...36, 39, 46) seitlich der kleinen Fläche (18, 32, 38) des genannten transparenten Körpers (13, 20, 37), derart, daß in den transparenten Körper (13, 20, 37) von hinten einfallendes Licht durch die kleine Fläche (18, 32, 38) an seinem vorderen Ende austreten und auf ein Objekt (4) gerichtet werden kann, und daß von dem Objekt (4) reflektiertes Licht in die transparente Schicht (15, 21, 24...27, 41, 42) durch deren kleine Fläche (17, 22, 33...36, 39, 40) einfallen und zu einem Lichtdetektor (19, 23, 28...31, 45) geleitet werden kann, mit dem die transparente Schicht (15, 21, 24...27, 41,· 42) optisch verbunden ist.

2. Apertur für ein optisches Nah-Feld Abtastmikroskop mit einem ersten optisch transparenten Körper (46, 51), der mit einer opaken Schicht überzogen ist, mit Ausnahme einer kleinen Fläche (47, 50) an seinem vorderen Ende, dadurch gekennzeichnet, daß wenigstens ein zweiter, spitzer, optisch transparenter Körper (48, 52&ellipsis55), der mit Ausnahme einer kleinen Fläche 49, 56...59) seitlich der kleinen Fläche (47, 50) des genannten transparenten Körpers (46, 51) mit einer opaken Schicht bedeckt ist, derart, neben dem genannten ersten transparenten Körper (46, 51) angeordnet ist, daß in den ersten transparenten Körper (46, 51) von hinten einfallendes Licht durch die kleine Fläche (47, 50) an seinem vorderen Ende austreten und auf ein Objekt (4) gerichtet werden kann, und daß von dem Objekt (4) reflektiertes Licht in den zweiten transparenten Körper (48, 52...55) durch dessen kleine Fläche (49, 56...59) einfallen und zu einem angeschlossenen Lichtdetektor geleitet wecden kann.

3. Apertur gemäß Anspruch 1, dadurch gekennzeichnet, daß die optisch transparente Schicht (15, 21, 24...27, 41, 42) gegen die kleine Fläche (17, 22, 33...36, 39, 40) bis auf eine Dicke von einem

Zwanzigstel der Wellenlänge des benutzten Lichts abgeschrägt ist.

4. Apertur gemäß Anspruch 2, dadurch gekennzeichnet, daß der zweite transparente Körper (48, 52...55) gegen die kleine Fläche (49, 56...59) bis auf eine Dicke von einem Zwanzigstel der Wellenlänge des benutzten Lichts abgeschrägt ist.

5. Apertur gemäß Anspruch 1, dadurch gekennzeichnet, daß der genannte transparente Körper (20) einen rechteckigen Querschnitt aufweist und über der genannten ersten opaken Schicht teilweise mit einer transparenten Schicht (21) bedeckt ist, die so abgeschrägt ist, daß eine durch ihbre schmale Öffnung (22) einfallende Lichtewelle zu einem einzelnen Lichtdetektor (23) geleitet wird, der mit der genannten transparenten Schicht (21) verbunden ist.

6. Apertur gemäß Anspruch 1, dadurch gekennzeichnet, daß die Seiten des genannten transparenten Körpers (20) mit zwei oder mehr transparenten Schichten (24...27) versehen sind, deren jede an einem Ende mit einem zugeordneten Lichtdetektor (28...31) verbunden ist und am andern Ende kleine Flächen (33...36) bildet, die symmetrisch um die kleine Fläche (32) auf dem transparenten Körper (20) angeordnet sind.

7. Apertur gemäß Anspruch 6, dadurch gekennzeichnet, daß der transparente Körper (20) einen quadratischen Querschnitt aufweist, und daß vier Lichtleiter (24...27) in kleinen Flächen (33...36) enden, die kreuzförmig angeordnet sind.

8. Apertur gemäß Anspruch 1, dadurch gekennzeichnet, daß die transparente Schicht (15) optisch mit einem kreisförmigen Lichtdetektor verbunden ist.

9. Apertur gemäß Anspruch 1, dadurch gekennzeichnet, daß der genannte transparente Körper (37) auf gegenüberliegenden Seiten, auf seiner opaken Schicht ein Paar transparenter Schichten als Lichtleiter (41, 42) trägt, die in einem Verbindungsstück (43) zusammenlaufen, das zu einem Lichtdetektor (45) führt, wobei einer der Lichtleiter (41, 42) einen optischen Phasenschieber (44) aufweist.

10. Apertur gemäß Anspruch 9, dadurch gekennzeichnet, daß die genannten Lichtleiter (41, 42) kleine Flächen (39, 40) aufweisen, die auf beiden Seiten der kleinen Fläche (38) des transparenten Körpers (37) angeordnet sind.

11. Apertur gemäß Anspruch 2, dadurch gekennzeichnet, daß der genannte erste trasnparente Körper (46, 51) und der genannte zweite transparente Körper (48), oder die genannten zweiten Körper (52...55) von einem optischen Material umgeben sind, nämlich von niedrigschelzendem Metall.

12. Apertur gemäß Anspruch 2, dadurch gekennzeichnet, daß der genannte erste transparente Körper (46, 51) und/oder der zweite transparente Körper (48), oder die genannten zweiten Körper (52...55) aus Glasfasern bestehen.

Revendications

1. Une ouverture pour microscope optique à balayage à champ proche, comportant un corps optiquement transparent (13, 20, 37) revêtu d'une première couche opaque (14), à l'exception d'une petite surface (18, 32, 38) à son extrémité frontale, caractérisée en ce que cette première couche opaque (14) est au moins partiellement recouverte d'une couche (15, 21, 26, 41, 42) d'un milieu optiquement transparent qui est lui-même recouvert d'une seconde couche opaque (16), à l'exception d'une petite surface (17, 22, 33,..., 36, 39, 40) située latéralement par rapport à la petite surface (18, 32, 38) du corps transparent (13, 20, 37), de sorte que la lumière pénétrant par l'arrière dans le corps transparent (13, 20, 37) puisse sortir par la petite surface (18, 32, 38) à l'extrémité frontale de celui-ci et soit dirigé sur un objet (4), et que la lumière réfléchie par cet objet (4) puisse pénétrer dans ladite couche transparente (15, 21, 24,...,27, 41, 42) par la petite surface (17, 22, 33,..., 36, 39, 40) de celle-ci et soit guidée vers un détecteur de lumière (19, 23, 28,..., 31, 45) auquel la couche transparente (15, 21, 24,..., 27, 41, 42) est optiquement reliée.

2. Une ouverture pour microscope optique à balayage à champ proche, comportant un corps optiquement transparent (46, 51) revêtu d'une première couche opaque, à l'exception d'une petite surface (47, 50) à son extrémité frontale, caractérisée en ce que l'on dispose au moins un second corps optiquement transparent (48, 52,..., 55), pointu, revêtu d'une couche opaque à l'exception d'une petite surface (49, 56,..., 59) située latéralement par rapport à la petite surface (47, 50) du premier corps transparent (46, 51), juxtaposé au premier corps transparent (46, 51), de sorte que la lumière pénétrant par l'arrière dans le premier corps transparent (46, 51) puisse sortir par la petite surface (47, 50) à l'extrémité frontale de celui-ci et soit dirigé sur un objet (4), et que la lumière réfléchie par cet objet (4) puisse pénétrer dans le second corps transparent (48, 52,..., 55) par la petite surface (49, 56,...,59) de celui-ci et soit guidée vers un détecteur de lumière associé.

3. L'ouverture de la revendication 1, caractérisée en ce que la couche optiquement transparente (15, 21, 24,...,27, 41, 42) est rétrécie en direction de sa petite zone (17, 22, 33,..., 36, 39, 40) jusqu'à une épiasseur d'environ un vingtième de la longueur d'onde de la lumière utilisée.

4. L'ouverture de la revendication 2, caractérisée en ce que le second corps transparent (48, 52,..., 55) est rétréci en direction de sa petite zone (49, 56,..., 59) jusqu'à une épaisseur d'environ un vingtième de la longueur d'onde de la lumière utilisée.

5. L'ouverture de la revendication 1, caractérisée en ce que le corps transparent (20) a une section rectangulaire et en ce qu'il est partiellement recouvert par une couche transparente (21) par dessus la première couche opaque, la couche transparente (21) étant biseautée de telle sorte qu'une onde lumineuse entrant par sa petite surface (22) soit guidée vers un détecteur de lumière unique (23) relié à ladite couche transparente (21).

6. L'ouverture de la revendication 1, caractérisée en ce que les côtés du corps transparent (20) sont pourvus de deux couches transparentes (24,..., 27) ou plus, chacune d'entre elles étant reliée à l'une de ses extrémités à un détecteur de lumière associé (28,..., 31) et formant à l'autre extrémité des petites surfaces (33,..., 36) disposées avec une répartition symétrique autour de la petite surface (32) du corps transparent (20).

7. L'ouverture de la revendication 6, caractérisée en ce que le corps transparent (20) a une section droite carrée, et en ce que quatre guides d'onde (24,..., 27) se terminent par des petites surfaces (33,..., 36) disposées selon une configuration cruciforme.

8. L'ouverture de la revendication 1, caractérisée en ce que la couche transparente (15) est optiquement reliée à un détecteur de lumière circulaire (19).

9. L'ouverture de la revendication 1, caractérisée en ce que ledit corps transparent (37) porte sur des faces opposées, par dessus sa couche opaque, une paire de couches transparentes formant guide de lumière (41, 42) reliées par une jonction (43) menant à un détecteur de lumière (45), l'un de ces guides de lumière (41, 42) étant pourvu d'un déphaseur optique (44).

10. L'ouverture de la revendication 9, caractérisée en ce que lesdits guides de lumière (41, 42) possèdent des petites surfaces (39, 40) situées chacune de part et d'autre de la petite surface (38) dudit corps transparent (37).

11. L'ouverture de la revendication 2, caractérisée en ce que ledit premier corps transparent (46, 51) et ledit second corps transparent (48) ou lesdits seconds corps transparents (52, 55) sont entourés par un matériau optique, notamment un métal à bas point de fusion.

12. L'ouverture de la revendication 2, caractérisée en ce que ledit premier corps transparent (46, 51) et/ou ledit second corps transparent (48) ou lesdits seconds corps transparents (52, 55) sont formés de fibres de verre.

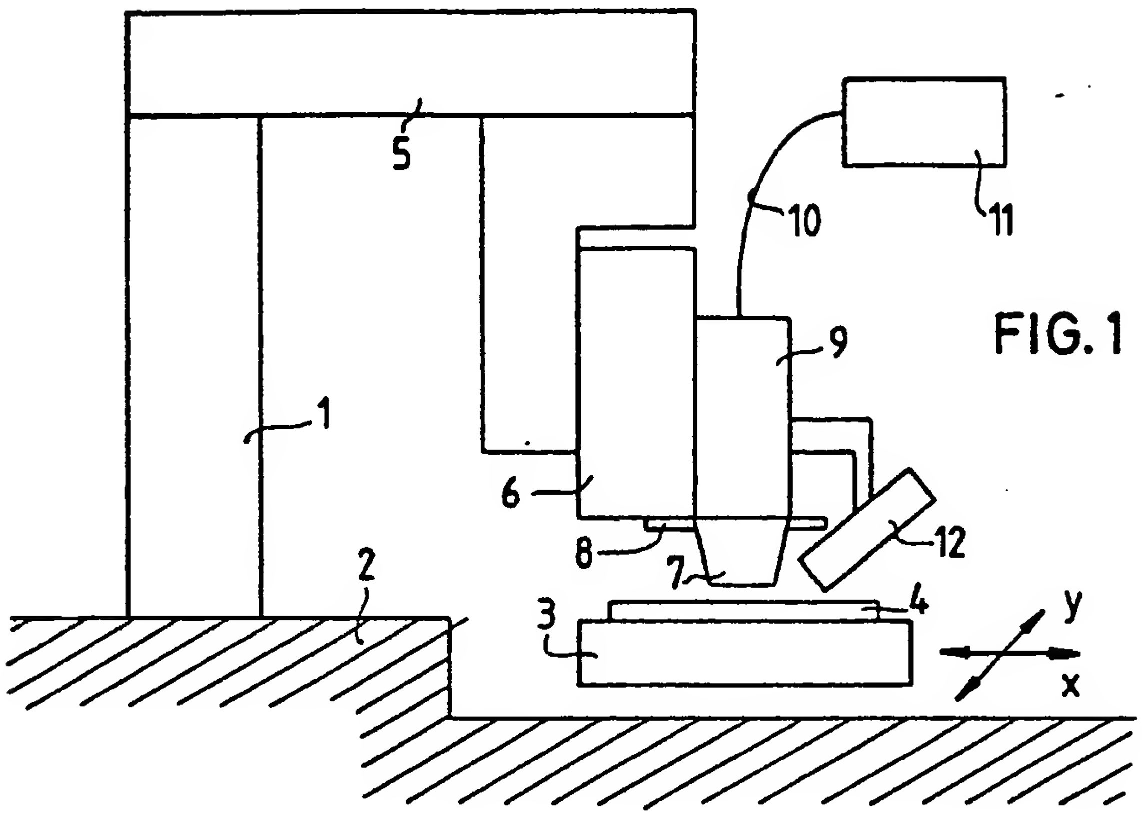

FIG. 1

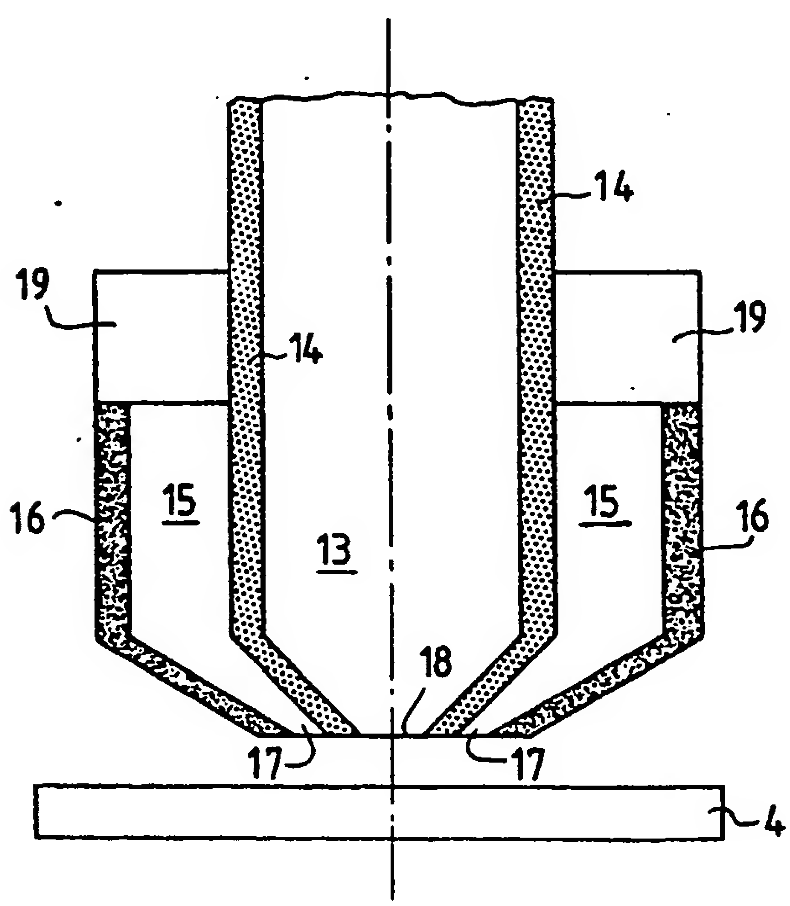

FIG. 2

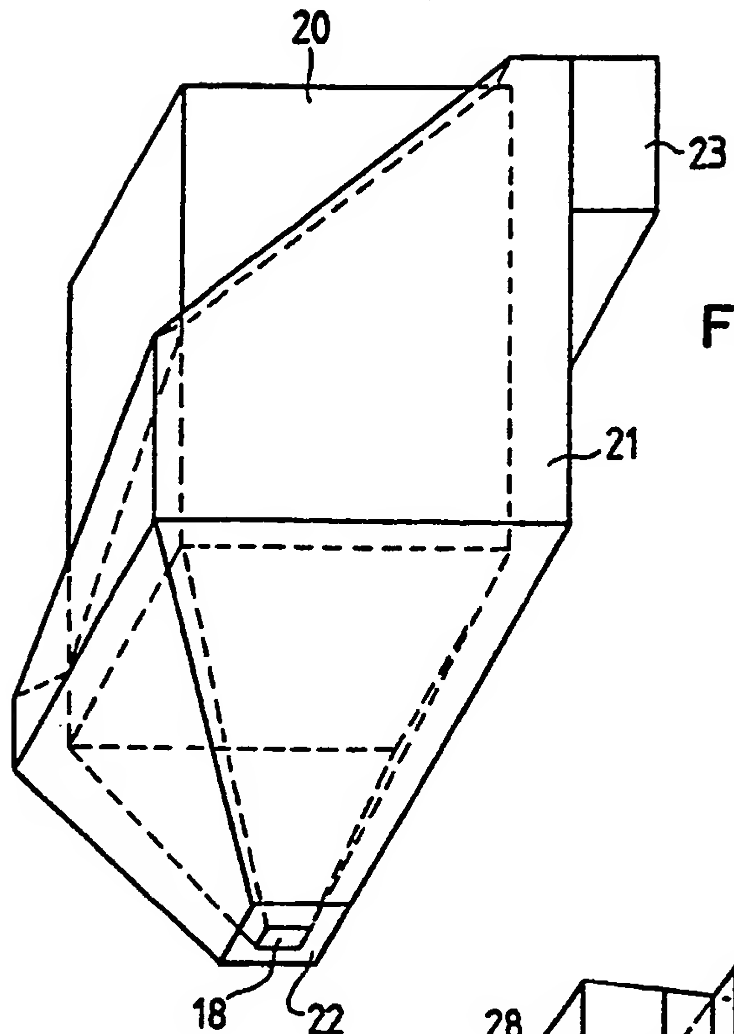

FIG. 3

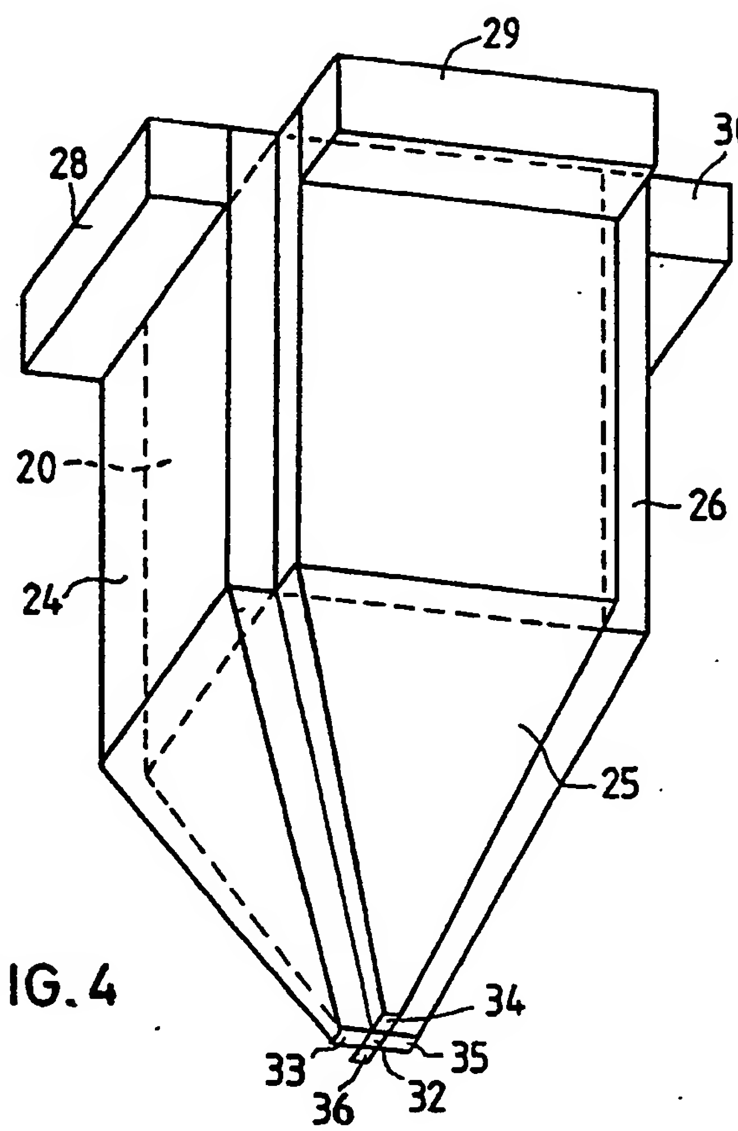

FIG. 4

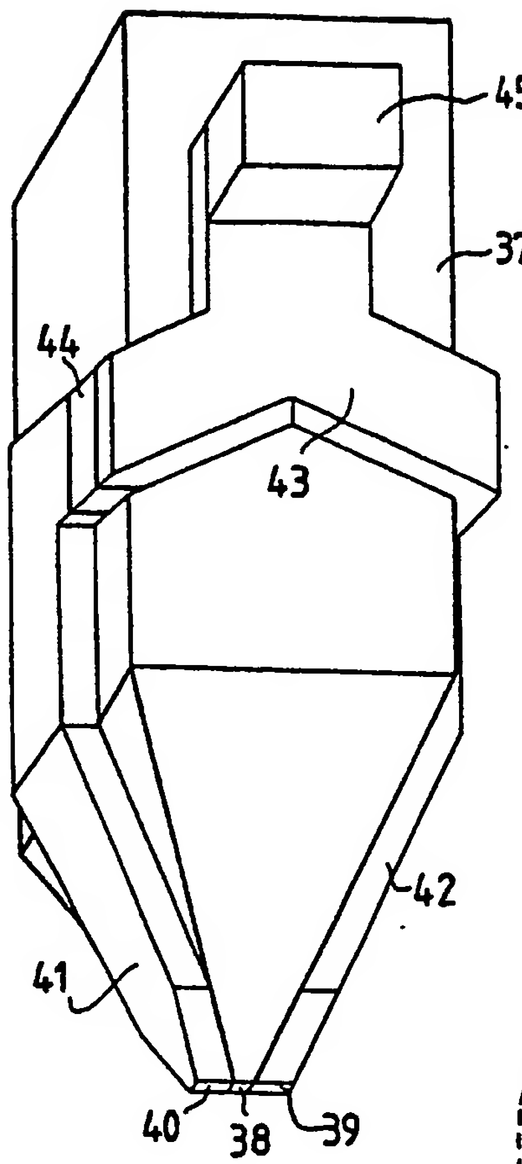

FIG.5

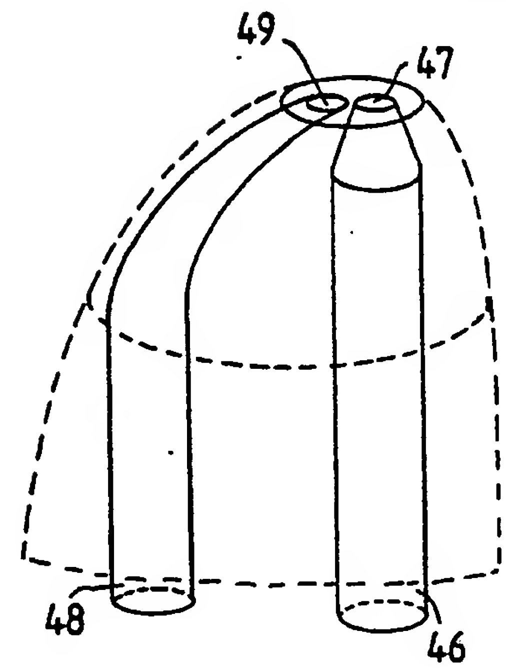

FIG.6

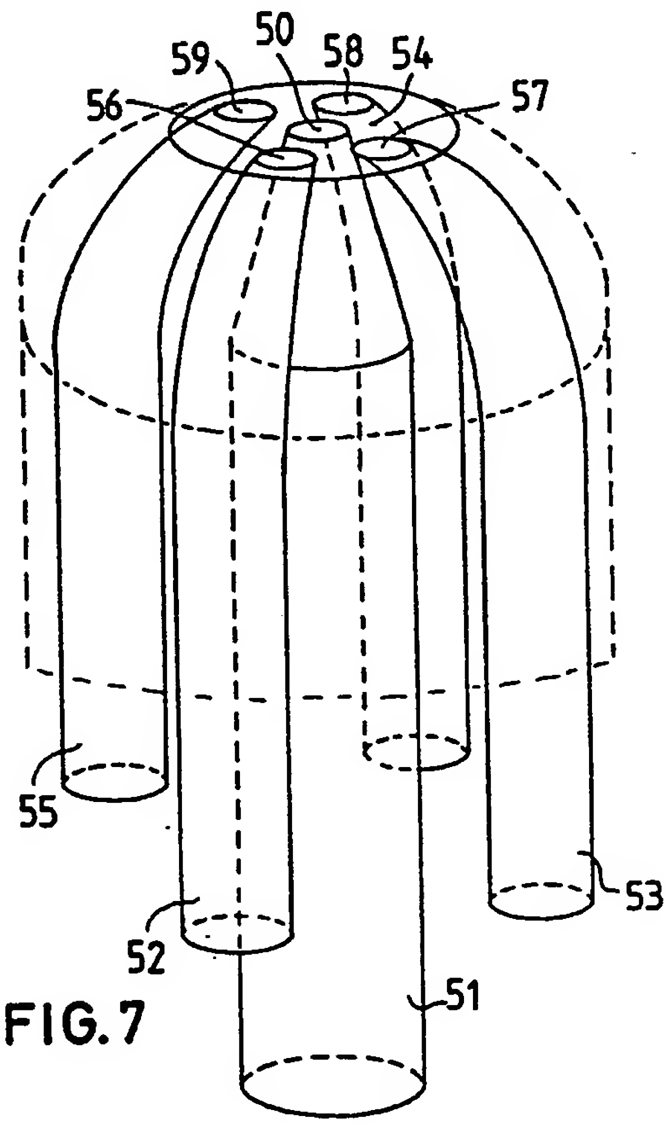

FIG.7